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RECENT DEVELOPMENTS IN UNDERSTANDING FIVE-POWER-LAW CREEP IN METALS

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ABSTRACT– This work describes recent advances on the effects of subgrain boundaries on elevated-temperature plasticity. Particular attention is devoted to recent developments regarding internal back-stresses. This will include discussions of recent convergent beam electron diffraction (CBED) experiments on metals to evaluate internal stresses in association with dislocation heterogeneities.

INTRODUCTION: Over extended elevated temperature (and strain-rate) ranges, pure metals and M-type alloys exhibit 5-power-law creep (Kassner and Perez-Prado [2000]). This paper reviews the established experimental trends that relate subgrain boundaries to 5-power-law creep behavior, and current interpretations of these trends and, most importantly, to illustrate that recent experiments appear to mandate a new understanding of the influence of subgrain boundaries on 5-power-law creep behavior.

DISCUSSION: Above about 0.6 T_m, metals and M-type alloys undergo (creep) plasticity that can be quantitatively described by:

$$\dot{\varepsilon}_{ss} = A \exp\left(-Q_{sd}/kT\right)(\sigma/E)^5 \qquad (1)$$

where A is a constant, Q_{sd} is the activation energy for lattice self-diffusion. A detailed mechanism rationalizing the details by which dislocation climb (climb-rate is controlled by Q_{sd}) is important has not been clearly established. The proposed mechanisms can be divided into two broad "categories". The first group suggests that subgrains or the low-misorientation (1-2°) interfaces that evolve during creep plasticity are vital. Often the concept of a backstress from subgrain walls is included in the detailed theory. The opposing view considers that subgrain walls are unimportant, that these low energy configurations have a smaller influence than the dislocations of the Frank network. In the past decade it appears that the majority of active creep plasticity investigators have favored subgrain-based mechanisms. However, earlier and recent experiments and analysis by the authors of this paper have offered clear support for network (non-interface-based) theories, and these are briefly discussed below.

Microstructure Manipulation Experiments: First, at ambient temperature, it is widely acknowledged that hardening occurs by increased dislocation density, ρ, and that the flow stress can be related to the dislocation density, ρ, by:

$$\tau = \tau_0 + \alpha\, Gb(\rho)^{0.5} \; . \tag{2}$$

Kassner, Miller and Sherby [1982] measured the isolated effect of dislocations on the elevated temperature strength of 304 stainless steel (M-type alloy) at a variety of temperatures and strain rates. It was later demonstrated that this data can be reasonably described by the form of Eqn. (2). It was also established that high purity aluminum has an elevated temperature strength that can be expressed in the classic form of Eqn. (2) as discussed in Kassner and Perez-Prado [2000]. Equation (2) may be applicable to other metals and alloys as well.

Grain Size Studies: Second, it has been suggested that subgrains strengthen in a manner analogous to grain-boundaries at ambient temperature. If this is the case, then we would expect subgrain strengthening to obey a Hall-Petch relationship. Studies found that grain size strengthening occurs in Al at high temperatures and can be described by the Hall-Petch equation. If the "subgrain strengthening" data is described by a Hall-Petch type equation, then the k_y values would be roughly 2.5 times larger than for grain-size strengthening. Extrapolation of the data of the strength of annealed polycrystals at large and moderate grain sizes to small sizes suggests that the *subgrain structures are associated with higher strength*, presumably due to the hardening from the Frank dislocations in the subgrain.

Large Strain Studies: Third, if subgrain boundaries are important, it would suggest that the details (misorientation angle, θ) of the boundaries would affect the creep properties. However, this conclusion is not consistent with recent observations regarding geometric-dynamic recrystallization (GDX) at 0.7 T_m in Al (Kassner and McMahon [1987]). With GDX the original starting grains elongate with large plastic strains. Although the total number of grains does not change, the high misorientation angle (grain boundary) interface area increases substantially. Here up to 1/3 of all subgrain facets originally of 1° misorientation, or so, are replaced by HABs of 20-30° misorientation. Despite this, the flow stress does *not* change.

Internal Stress Studies: Finally, one of the important suggestions within the creep community is that of the internal (or back) stress which, of course, has been suggested for plastic deformation in general. Several investigators advocated the simple case where 'hard' (high dislocation density walls or cells) and soft (low dislocation density) elastic-perfectly-plastic regions are compatibly sheared in parallel. Basically, the analysis shows that each component yields at a different stress, and hence, the material is under a heterogeneous stress-state with the cell walls (subgrains at high temperatures) having the higher stress. The details of many creep theories rely on high internal stresses. Some suggest backstresses are, perhaps, a factor of 20 higher than the applied stress. Another concept of backstress is related to dislocation configurations. With this model, the subgrain boundaries that form from dislocation reaction bow under the shear stress and this creates relatively high local stresses. These are all discussed in Kassner and Perez-Prado [2000].

Convergent beam electron diffraction (CBED) can probe smaller areas with a 20-100 nm beam size rather than the entire sample as with x-rays and is potentially more accurate in assessing internal stresses in association with dislocation heterogeneities. Recent CBED experiments by the authors on unloaded Al single crystals deformed at a five-power temperature/strain-rate regime did *not* detect the presence of any residual stresses (to within 8 MPa). These are illustrated in Fig. 1.

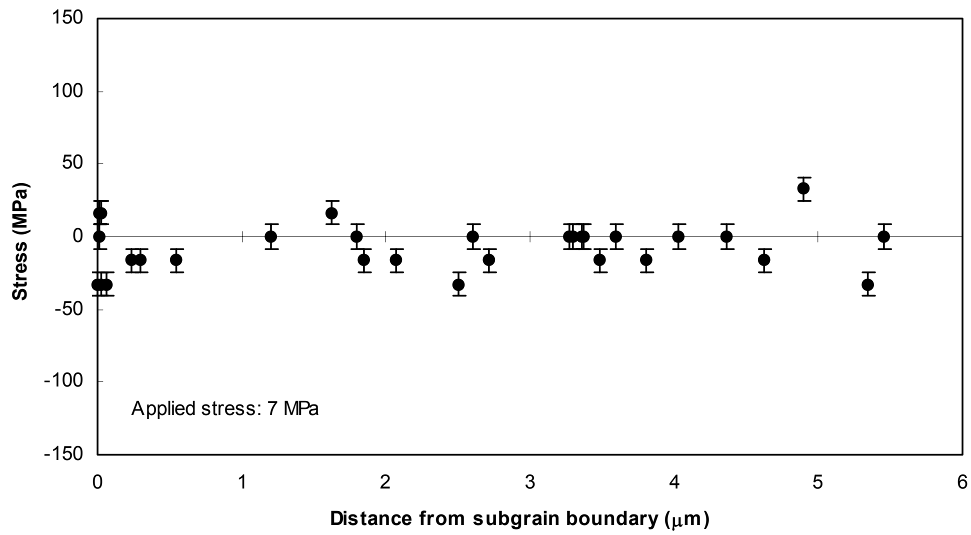

Fig. 1 The lattice parameter and corresponding stress determinations based on the CBED in single crystal Al deformed for steady-state within the five-power-law creep regime.

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REFERENCES:

Kassner, M.E. and McMahon, M.E. 1987, “The Dislocation Microstructure of Aluminum Deformed to Very Large Steady-State Creep Strains,” Metall. Trans., **18A**, 835.

Kassner, M.E. and Perez-Prado, M.T. 2000, “Five-Power-Law Creep in Single Phase Metals,” Prog. Mater. Sci., **45**, 1.

Kassner, M.E., Miller, A.K., and Sherby, O.D. 1982, “The Separate Roles of Forest Dislocations and Subgrains in the Isotropic Hardening of Type 304 Stainless Steel,” Metall. Trans., **13A**, 1977.